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In search for a canonical design ABL stability class for wind farm turbines

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Abstract. Production as well as loading of wake exposed wind turbines is known to depend significantly on stability of the Atmospheric Boundary Layer (ABL), which adds a new dimension to design of wind farm turbines. Adding this new aspect in wind turbine design makes the number of design cycle computations to blow up with a factor equal to the number of representative stability bin classes. The research question to be answered in this paper is: Can an ABL stability probability distribution in a meaningful way be collapsed into a representative design stability class as based on a (predefined) confidence level.

1. Introduction

Loading of solitary wind turbines (WTs) are known to be affected by ABL stability [1], where especially tower and rotor loads under diabatic wind conditions are increased compared to the neutral case. For wind turbines operating in wind farm (WF) conditions the influence of ABL stability on production [2] and loads [3] are further enhanced. This is primary due to wake dynamics being highly sensitive to ABL stability conditions [4, 5].

The IEC standard [6] for wind turbine loads describes a load envelope, which a turbine design has to comply with. However, the present version of this code does not consider the ABL stability aspect. A straight forward inclusion adds a new dimension to the design problem and thus in turn leads to a considerable additional computational load. This motivates to investigate whether or not it is possible to collapse an ABL stability probability distribution into a site specific design stability class, whereby the computational load will be left unchanged.

For solitary turbines such a collapse is a priory not considered to be possible. This is because the various turbine main components react differently to a specific ABL stability condition [1]. This links to both the deterministic part of the wind field and the stochastic part (i.e. the turbulence) being affected by diabatic effects, and that these are contradicting factors in a load context, such that component loads mainly depending on the deterministic loading (i.e. the mean wind shear profile) and component loads mainly depending on turbulence respond differently to a specific ABL stability condition. However, for WF turbines the ABL stability dependent wake dynamics is a prominent load generator, resulting in a somewhat more coherent dependence of component loads on ABL stability, and thereby potentially opens for definition of a meaningful *design* ABL stability class.

We will investigate this by using a very simple generic wind farm populated with only two 5MW turbines and operate these under a stability climatology representing an off-shore site. Moreover, we



will limit the study to a simplified design envelope consisting of *normal operation* fatigue driven load cases only (i.e. DCL 1.2. specified in [1]).

2. Approach

The basic idea is to base the investigation on a mapping of the ABL stability probability density function (pdf) on selected pdf's associated with predefined load sensors on turbine main components (i.e. tower, main shaft and blades); and moreover to be able to consistently track back arbitrary load (sensor) quantiles to quantiles of the driving stochastic forcing under consideration (i.e. ABL stability), thus facilitating the definition of a representative design stability class on a rational basis for a pre-specified confidence level.

The treatment of the resulting single-input multiple-output system is based on a classical theorem for transformation of stochastic variables. Let a stochastic variable, ξ , characterize some type of external inflow conditions (e.g. ABL stability), and l be a stochastic variable characterizing some resulting wind turbine structural response (e.g. aggregated fatigue equivalent moment corresponding to the selected *simplified design envelope*, DCL 1.2, associated with a specific main component cross section). Thus

$$l = L(\xi)$$

where $L(\bullet)$ is a transformation function which relates the external wake and affected wind loading with the structural response signal in question. The relationship between the pdf of ξ , f_ξ , and the requested pdf of l , f_l , is given as [7]

$$f_l(l) = \sum_{i=1}^N \frac{f_\xi(\xi_i)}{|L'(\xi_i)|}$$

where $(\bullet)'$ denotes differentiation with respect to ξ , and N is the number of ξ_i -roots satisfying the equation

$$l = L(\xi_i)$$

for *specific choices* of l .

Once the design envelope load transformation is defined, the “inverse tracking”, relating an arbitrarily selected design envelope load quantile to quantiles of the driving stochastic forcing in a rational manner, is straight forward. This tracking is, however, *only unique* if the number of roots, N , in the above equation equals one. In this case, the inverse tracking is given by

$$\xi = L^{-1}(l)$$

The case where N is larger than one thus poses a “selection problem”, which in the end will rely on a motivated definition. A logical choice among the countable number of possible candidates, ξ_i , are the particular ξ_i contributing the most to the load quantile in question, ξ_m , i.e.

$$\xi_m = \left\{ \xi_m \left| \frac{f_\xi(\xi_m)}{|L'(\xi_m)|} = \max_i \frac{f_\xi(\xi_i)}{|L'(\xi_i)|} \right. \right\}$$

The study will be based on a 98% confidence level.

3. The case study

Obviously, real WFs represent a broad range of topological variations, which in turn will affect the loading of the individual WF WTs. The present study aims at investigating *if* all ABL stability effects can be taken into account in WF design computations by defining an appropriate *design stability class*, but also, if the answer to this research question is ‘yes’, to give some guidance in the definition in such a design class.

3.1. Generic WF layout topology

To fulfil the purpose stated above we need to define a representative generic class of WF topologies to investigate. Considering the closest upstream turbine as the most load influencing, we will define the simplest possible generic WF topology – namely a WF consisting of only two turbines with three different distances between these representing respectively small (3D), medium (5D) and large (8D) WT inter-spacings.

3.2. Wind direction rose

In an attempt to include impact from various *wind directions* on the wake loading the following wake cases are considered for each of the WF class elements (i.e. turbine inter-spacings):

- A no wake case;
- Partial wake inflow cases with inflow angles relative to the imaginary line connecting the two turbines defined as: $\{\pm i \times [\text{Arctan}(D/jD) + \text{Arctan}(TI)]/5\}$; $i = 0, 1, \dots, 5$; where j takes the values 3, 5 or 8 according to the turbine spacing in question.

The no-wake case and each of the partial wake inflow cases are assumed to have *identical probability* for occurrence – i.e. uniform pdf of the individual inflow cases.

3.3. ABL stability classification

To quantify the ABL stability condition, we adopt the classification scheme proposed in [4], in which 7 stability classes are defined in terms of the Monin-Obukhov length, L_M , expressing the height where production of mechanical and convective turbulence is equal, and thus offering a natural way to quantify the degree of dominance of buoyancy over mechanical and shearing effects. The stability classification scheme is summarized in Table 1.

Table 1. Stability classification scheme.

Stability identifier	Stability class description	$1/L_M$ range
-3	Very unstable	[-0.02; -0.01]
-2	Unstable	[-0.01; -0.005]
-1	Near neutral/unstable	[-0.005; -0.002]
0	Neutral	[-0.002; 0.002]
1	Near neutral/stable	[0.002; 0.005]
2	Stable	[0.005; 0.02]
3	Very stable	[0.02; 0.1]

3.4. Ambient wind conditions

With the stability classification in place we are ready to define the ambient wind climate – i.e. the deterministic mean wind field and the turbulence – conditioned on the ABL stability condition. Basically, the ambient wind conditions are defined in accordance with IEC61400-1 – in this case with the *off-shore* wind conditions being defined by IEC class 1B. The wind classes in IEC61400-1, however, relates to neutral ABL conditions only.

For non-neutral conditions, the deterministic mean wind speed, $U(z)$, as function of height, z , is obtained by “matching” the IEC power law wind profile, defined by its exponent α , with conventional stability corrections [12, 13]. For *stable* conditions this approach leads to the following definition

$$U(z) = U_{hub}(z/z_{hub})^\alpha + \frac{5U_{hub}}{\ln(z_{hub}/z_0)} \frac{z}{L_M} ; 0 \leq \frac{z}{L_M} \leq 1$$

For *unstable* conditions we arrive at this definition

$$U(z) = U_{hub} \left(\frac{z}{z_{hub}} \right)^\alpha + \frac{U_{hub}}{\ln \left(\frac{z_{hub}}{z_0} \right)} \left\{ -\ln \left[\frac{1+x^2}{2} \left(\frac{1+x}{2} \right) \right] + 2\text{Arctan}(x) - \frac{\pi}{2} \right\}; \quad -2 \leq \frac{z}{L_M} \leq 0$$

with

$$x = \left(1 - 16 \frac{z}{L_M} \right)^{1/4}$$

Turbulence under non-neutral conditions also requires special attention and is modeled using a newly developed buoyancy-dependent spectral tensor [10], which degenerates to the classical Mann spectral tensor for neutral conditions. The parameters of the buoyancy dependent spectral tensor are, for each stability class, obtained from fitting a set of model auto- and cross spectra to respective spectra obtained from full-scale measurements. These are subsequently scaled to mimic IEC turbulence conditions in the non-neutral regime.

3.5. The stability climatology

The last element required to define the case study is the pdf of the ABL stability condition conditioned on the mean wind speed. For the off-shore case, a representative pdf is obtained by analyzing 167.762 10-minute series from a meteorological tower at the Danish Horns Rev site. The stability classification is performed using the AMOK approach [15] with temperature input from a sensor located well within the surface layer (i.e. at 13m above sea level (asl)), and wind speed input from a top-mounted cup anemometer at 62m asl.

The resulting conditional stability pdf's were subsequently "transformed" to be conditioned on the mean wind speed at hub height level – i.e. 90m asl. The data set covered the mean wind speed range [4; 25]m/s with an acceptable data coverage. As an illustration the stability pdf referring to the mean wind speed bin [10; 11]m/s is shown in Figure 1.

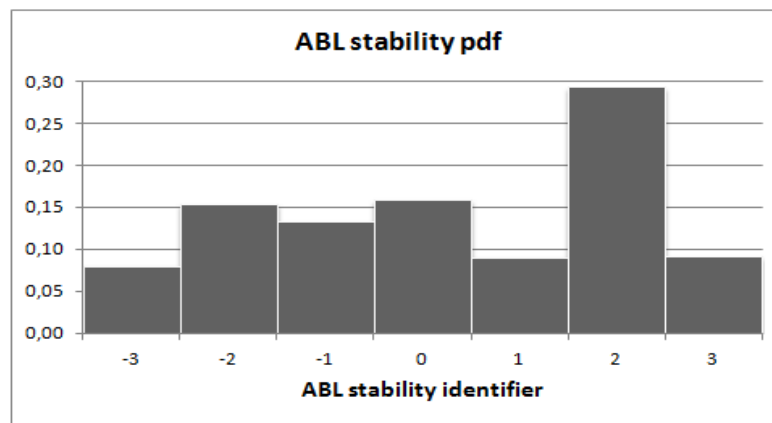


Figure 1: Stability pdf conditioned on the mean wind speed bin [10; 11]m/s.

4. Numerical approach

The transformation L defined in Section 2 is determined *numerically* using the state-of-the-art aeroelastic code HAWC2 [8] together with the NREL 5MW turbine [11] with a rotor diameter (D) of 126m and a hub height equal to 90m. The structural part of HAWC2 is based on a multi-body formulation using the floating frame of reference method. Each body includes its own coordinate system with calculation of internal inertia loads, when this coordinate system is moved in space, and hence large rotation and translation of the body motion are accounted for.

The WT sensors defined for the analysis are: blade flap bending moment; rotor yaw moment; and tower bottom fore-aft moment. These three sensors are selected because they reflect the most

significantly wake driven loading of turbine main components, and because this sensor choice allows for a direct comparison with the results obtained in [1] for a solitary turbine. The focus of the study is on turbine *fatigue loads*, and consequently all sensor signals are post processed to give fatigue equivalent moments as based on the traditional Palmgren-Miner linear damage accumulation rule [16]. Note, that the transformation L includes the entire numerical processing leading from “inflow condition” to specific main component fatigue moments.

The wake affected inflow fields are generated using the Dynamic Wake Meandering (DWM) model [9], in which ABL stability is included by adjusting the energy level of the meandering turbulence scales using the buoyancy dependent spectral tensor [10]. This approach is consistent with the major impact from buoyancy on the ABL turbulence structure being on large turbulent scales and has been validated in [4, 5].

Mean wind speeds in the range [5 m/s; 25 m/s], each with yaw errors of $(-10^\circ; 0^\circ; 10^\circ)$, are considered for the design envelope, and for each of such load case 6 realisations (i.e. 6 different turbulence seeds) are conducted to improve the statistical significance of the results by associating a sensor result with the arithmetic mean of the sensor results over the realizations. This leads to a total of 49896 aeroelastic computations for the off-shore case.

5. Results

Because of the discrete character of the derived response pdf's, we must adopt a suitable interpolation scheme in order to resolve relevant quantiles with sufficient accuracy. For this purpose we use a dedicated spline-like approach developed in [14], which assures that the probability mass, associated with a particular stability bin, is preserved using a suitable interpolation function of differentiability class C^3 .

Examples of (seed-averaged) fatigue equivalent response curves and their derivatives are shown in Figures 2 and 3 for the mean wind speed equal to 14m/s and associated with the off-shore case with medium size WF WT spacing (5D). The derivatives are determined using a second order central difference scheme except for the “end points”, where second order forward and backward approaches are used.

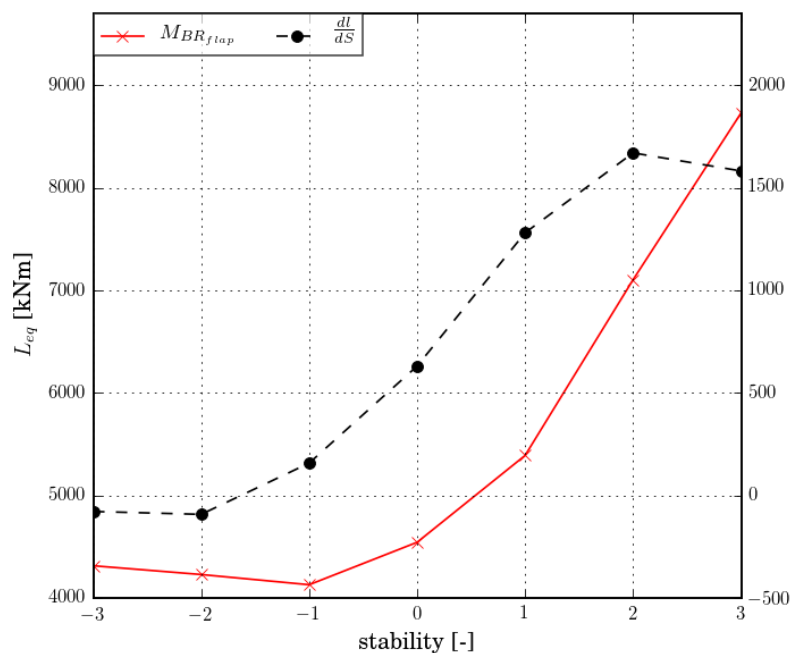


Figure 2: Load response function, M_{BRflap} (red), and its derivative, dL/dS (black), for the blade root flap moment as function of the stability identifier for the 5D off-shore case.

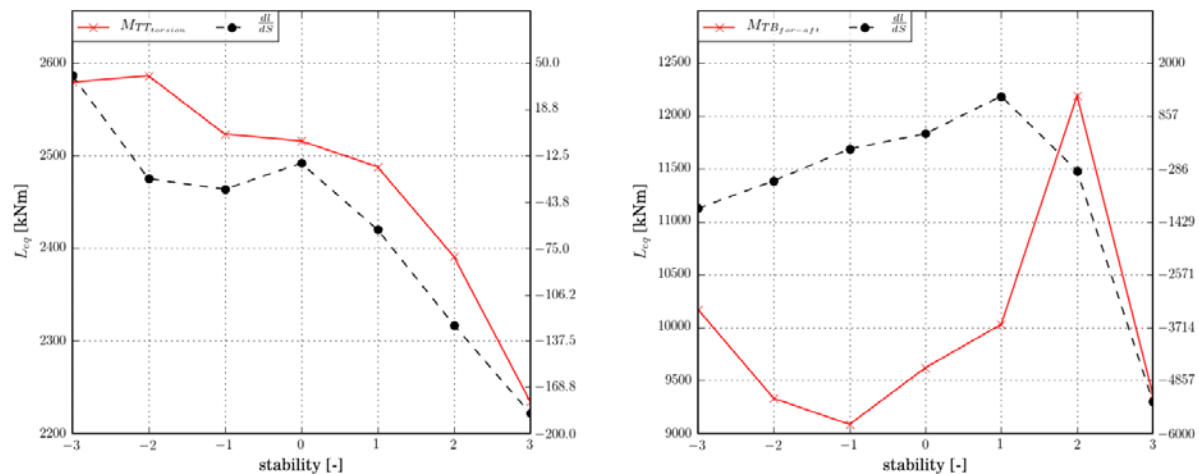


Figure 3: Load response functions, $M_{TTorsion} / M_{TBfor-aft}$ (red), and their derivatives, dL/dS (black), for rotor yaw and tower for-aft moments as function of the stability identifier for the 5D off-shore case.

Two observations are of significant importance here: 1) The blade root flap moment and the rotor yaw moment are (roughly) monotonic as function of the ABL stability measure, however, with gradients with respect to the stability measure having opposite sign. This is analogue to the solitary turbine case. 2) The tower for-aft moment displays a highly non-monotonic behaviour. Both observations are also true for other for other mean wind speeds as well as for other WT spacings. As a consequence of the first observation it is clear, that a *universal* design stability class, covering all turbine components, is not obtainable. The consequence of the second observation is that not even a collapse of an ABL stability probability distribution into *component specific* design stability classes is possible.

The latter aspect is contrary for a solitary turbine, and we consequently rephrase the research question of this paper by adding: *Can an ABL stability probability distribution in a meaningful way be collapsed into a representative component specific design stability class for a solitary turbine as based on a (predefined) confidence level.* If this is possible, it means that the computational burden will be considerable reduced compared to straight forward inclusion ABL stability as an additional design dimension but, however, increased by a factor of two compared to present practice, where ABL stability effects are not considered.

Concerning (seed-averaged) fatigue equivalent response curves in the *no-wake* case, the blade root flap moment behaves qualitatively as shown in Figure 3 – i.e. displaying a roughly monotonic behaviour as function of the stability measure. Concerning the tower yaw and the tower for-aft loading in the *no-wake* case, representative examples of (seed-averaged) fatigue equivalent response curves and their derivatives are shown in Figure 4 for the mean wind speed equal to 14m/s. Contrary to the wake cases, both tower moments now display a (roughly) monotonic behaviour as function of the stability parameter. These qualitative observations are mean wind speed independent.

With the load response functions and their derivatives in place, the corresponding fatigue load pdf's are now determined using the formalism described in Section 2. Continuing the selected example from above (i.e. WT no-wake case and mean wind speed equal to 14m/s) the corresponding fatigue load pdf's and cumulative distribution functions (cdf's) are shown in Figures 5 and 6 for respectively the blade root flap moment, the rotor yaw moment and the tower base for-aft moment.

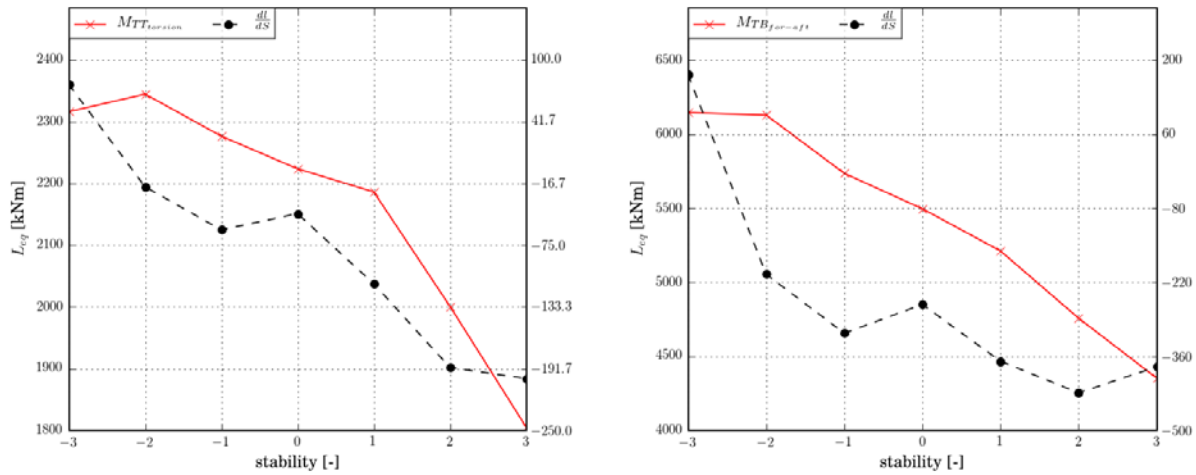


Figure 4: Load response functions, $M_{TTorsion} / M_{TBfor-aft}$ (red), and their derivatives, dl/dS (black), for rotor yaw and tower for-aft moments as function of the stability identifier for the no-wake case.

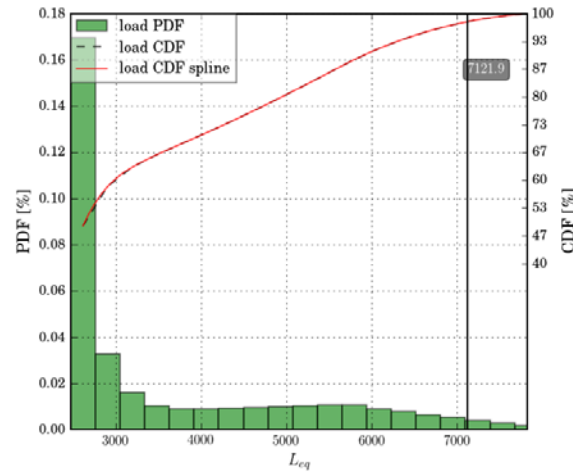


Figure 5: Load response pdf and cdf for the blade root flap moment for the no-wake case.

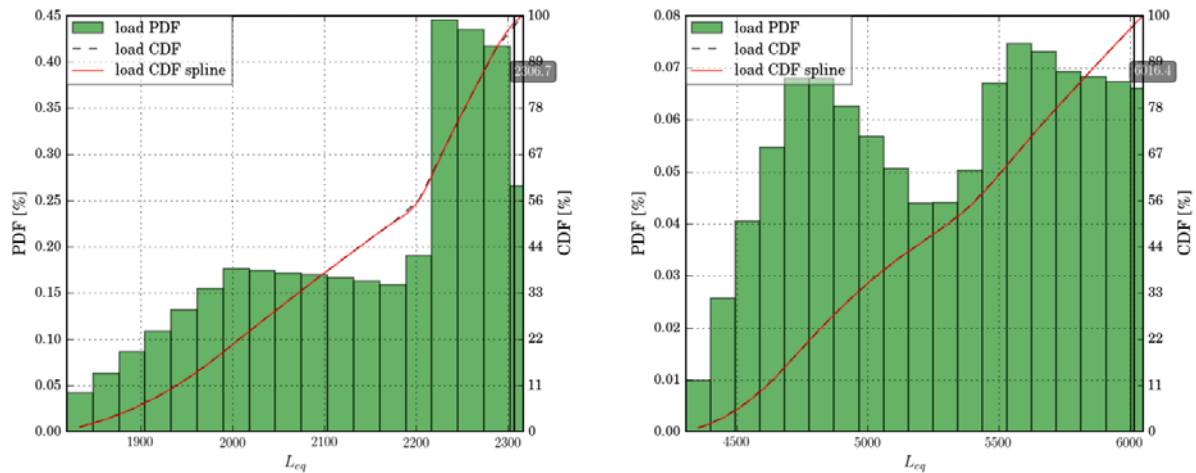


Figure 6: Load response pdfs and cdfs for the rotor yaw moment (left) and the tower base for-aft moment (right) associated with the no-wake case.

The sought *design stability class*, c_d , is a function of the mean wind speed U , the component load response l_i and the requested confidence level cl : $c_d = c_d(U, l_i, cl)$. This is because the stability climatology investigation of the Horns Rev data, as expected, shows that the stability pdf is highly dependent of the mean wind speed; because fatigue load impact of ABL stability is component dependent – i.e. in particular depends on whether the component is rotating in the ABL stability dependent flow field or not; and because the definition of the design stability class links directly to the confidence level. Adopting a 98% confidence level, the design stability class is thus described by the hyper-plane defined by $cl = 0.98$.

Analyzing the results it is observed, that within this hyper-plane the design stability class, c_d , depends on the mean wind speed and on the particular load sensor. The c_d variability with mean wind speed is significant as is the variability among on the one hand the blade root flap moment and on the other hand the tower bottom for-aft moment and the rotor yaw moment.

In a design simulation context, a mean wind dependent design stability class is perfectly acceptable, while mutual consistence among the component specific load sensors, which drive the design of the particular WT component, is a “must” for a given mean wind speed. To the degree that the sensor-dependent component design loads deviate mutually for a given mean wind speed, one option is to take a *conservative approach* ensuring that all design driving sensors adapt *at least* to the required confidence level. For this to be meaningful the relevant component design loads must respond in a reasonable coherent manner on the ABL stability measure, meaning that these are predominantly monotonic in the stability measure and furthermore with identical sign of the load gradient with respect to this stability measure. As stated above this is perfectly true component wise for the no-wake case.

Based on a conservative approach, resulting ABL *design stability class* identifier values are condensed into the recommendations given in Table 2, showing wind speed and component dependent c_d values for the *no-wake* case.

Table 2. Design stability class conditional on mean wind speed and turbine component.

Wind speed [m/s]	Blade (c_d)	Tower (c_d)
4	3	-3
6	3	-3
8	2	-2
10	3	-2
12	3	-2
14	3	-3
16	3	-3
18	2	-3
20	2	-3
22	2	-2
24	2	-2

6. Conclusions

The research question originally posed for this work is: *Can an ABL stability probability distribution in a meaningful way be collapsed into a representative design stability class (based on a predefined confidence level) for WTs operating in wake affected flow fields as in WFs.* To answer this question, we have defined a simple case study with the WF topology described by only two turbines operating in a variety of wake situations. The investigated layout topology includes three different WT spacings

– 3D, 5D and 8D – representing small, medium and large WT spacings, respectively. The stability climatology is defined from analyzing a huge amount of full scale data.

The analysis shows that the conjecture formulated in the introduction – i.e. that compared to solitary WT's the component loading of wake affected WT's display a somewhat more coherent dependence on ABL stability – is *not* true. On the contrary the analysis shows that wake affected loading of rotating and non-rotating WT components, respectively, display an equally in-coherent dependence on ABL stability as has previously been seen for solitary turbines and that, on top of that, especially the tower bottom for-aft moment displays a pronounced non-monotonic behavior as function of the stability parameter, which even hinder definition of component specific design stability classes.

This result fostered an extension of the research question of this paper, namely: *Can an ABL stability probability distribution in a meaningful way be collapsed into a representative component specific design stability class for a solitary turbine as based on a (predefined) confidence level.*

The analysis shows that this is indeed possible. Using the developed rational approach, two component specific *design stability classes*, conditioned on the ambient mean wind speed, have been defined; one for blade loads and one for tower loads.

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